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How Distributed Situation Awareness Influences Process Safety

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The increasing complexity of chemical processes, in terms of technological involvement, intensified with automation, has made the role and job of industrial operators more significant in terms of Process Safety. This work takes the concept of Distributed Situation Awareness (DSA), introduced by Stanton *et al.* (2006), and presents its application, adaptation, and influence on the process industry in general and on industrial operators in particular. DSA considers the importance of viewing the system as a whole by considering all the parts in the environment. The combination and interaction of different elements including field operators, control room operators, the artifacts with which they interact with each other and with different bits of information/data, and the communication among them are the basis on which the DSA of industrial operators founds. The decisions made by the operator are not only based on his/her understanding and mental model but they include the whole system. The paper shows how studying the operator as an individual only is not sufficient. Conversely, a holistic approach allows gathering most of the nuances of complex systems as the industrial plants are. A measurement method for DSA is proposed and a case study, *i.e.*, a refinery sub-section, aimed at identifying and devising specific DSA indicators, is presented. This work can help in reducing abnormal situations, near misses, and accidents arising from errors related to operators and their interaction with other operators and with various elements of the process industry.

1. Introduction

Since the beginning of industrial revolution in the 17th century, the growth of industries has never looked back (Ashton, 1948). Only in Europe in 2011, 539 billion euros was the revenue generated from the chemical industry, with about 1.1 million of employees (CEFIC, 2012). The growth and advancements in construction, equipment, unit operations, unit processes, and methods improved steadily with time. The last two decades have seen tremendous growth in technology and the nature of the processes have changed also. Increase in demand, production, and associated economic benefits encouraged the expansion of chemical, petrochemical, and refinery plants to expand their capacity. At the same time, several new humongous chemical plants emerged in different parts of USA, Europe, and later South America and emerging Asian countries. The growing capacities of chemical plants together with technological and automation integration resulted in new challenges, which were unforeseen by stakeholders, engineers, and designers. New terminologies found their way into the dictionaries of chemical industry, not in terms of only technical aspects, but from the perspective of the human (operator in this case). As a result, new challenges emerged, especially for the operators who deal with modern technology, contrary to practices in past, when systems were much simpler and less robust. Vicente (1999) states that "New Problems Demand New Approaches" (p. 17) and raises doubts concerning the human capacity to effectively utilize modern technology by asking "Do we know how to use it?" (p. 19).
The emergence of automated tools and their overly deployment in chemical industry has changed the nature of operators work. In the past, the systems were analogue and a casual visit at the plant site was sufficient to monitor the progress and production of plants. This approach is no longer feasible. The operators must stay *on their toes* to monitor, assess, and understand the incoming information from

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various sources and act/react accordingly. The decisions made by operators (who are scattered at different parts of the plant) define the outcome(s) of possible abnormal situations, near misses, or even accident events. Therefore, the study of operators' behavior and the concepts, which fall under the umbrella of human factors, is necessary to make the whole system safer. This paper takes a newly developed concept *i.e.*, Distributed Situation Awareness (Stanton *et al.*, 2006) and considers its implication in the world of process industry. The paper introduces the significance, impact, and implications of the concept of DSA for industrial operators and its relevance to *process safety*. Moreover, a unique method of measuring DSA is proposed and a case study from a refinery is presented for elucidation of the proposed measurement method of DSA in industrial operators.

2. Distributed Situation Awareness

Consider a system with multiple distributed control units (humans, actuators, automatons, etc.). In order to ensure safe and efficient operation one must focus on the interaction and coordination between the control units. When the control system involves humans that are able to perceive and understand the meaning of elements in the world around them, the system model must also encompass the characteristics of humans. Stanton *et al.* (2006) introduced the Distributed Situation Awareness (DSA) theory to show how situation awareness is established and maintained in distributed complex systems. Situation Awareness as defined by Endsley (1995) is "*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future*". The main assumption in DSA is that adaptive behavior is achieved through the coordination among system units. Hence, the focus of DSA is the whole system as opposed to focusing on the individuals/components in the organization (Salmon *et al.*, 2009a, 2009b). Each operator gets a unique personal perspective of the world and since work in distributed systems is (usually) highly specialized, there is no need for a fully shared understanding of the situation among operators. Distributed Situation Awareness is thus a system construct that according to DSA proponents resides in the whole system (Salmon *et al.*, 2009; Stanton *et al.*, 2006). Each component/individual has a unique understanding/mental mapping that must be compatible (but not identical) with other individuals in order to ensure successful coordination of work tasks. The idea of compatibility of individual's situation awareness also fits with the fact that different operators have specialized work tasks with their own goals, constraints, and requirements.

3. DSA and industrial operators

This work is a first attempt to connect two different domains (DSA and process industry) together as a step towards improvement of the performance of operators, which will ultimately result in safer operations. Formerly, the concept of Situation Awareness was applied to industrial operators (Nazir *et al.*, 2012). As different bits of information are distributed among operators, artifacts, and technological tools, we believe that implication of DSA of industrial operators is inevitable.

Industrial operators can be categorized according to their job location. Operators working in the field are called Field Operators (FOPs) and the ones working in the control room are called Control Room Operators (CROPs). Both CROPs and FOPs do not work alone and independently but need to engage in teamwork by using teamwork skills. Wilson *et al.* (2007) defined team work as "*a multidimensional, dynamic construct that refers to a set of interrelated cognitions, behaviors and attitudes that occur as team members perform a task that results in a coordinated and synchronized collective action*" (p. 5). During normal operations, there is periodic communication for collaborative actions between FOPs and CROPs to assure continuous and safe operations. The significance of this communication is much higher once uncertainties are introduced to the system and the operations get out of the normal operating domain. In case of abnormal situations, the sensitivity and impact of such a communication increases significantly. For example, an abnormality observed by a FOP, using his/her physical senses, must be reported to the CROP for necessary actions and/or instructions. The communication in this scenario is not only a matter of delivering a message but to weigh, analyze the problem/malfunction, and reach correct and timely decisions (Nazir *et al.*, 2012). The ultimate consequences of abnormal situations or accidents depend on the shared understanding, compatibility, and effective communication among operators. There are also cases where the communication among operators is intentionally avoided due to consolidated habits that are originated by either unsafe company policies or precarious equipment features. This was the case of the BP Texas refinery accident occurred in 2005 (Manca and Brambilla, 2012) where both FOPs and CROPs ignored that the liquid inside the column was accumulating dangerously because of a persistent misleading measurement that made them neither consider nor rely on the faulty data measured in the field. A clear and shared mental model and joint cognition can facilitate such communication and the subsequently necessary actions (Nazir *et al.*, 2012). It is necessary for operators to monitor recurrently the dynamics of the process and to make timely correct decisions based on their mutual comprehension deduced from the available information that is changing dynamically. At the same time, FOPs and CROPs are physically distant and surrounded by completely different environments and information. Under these conditions, the distributed nature of information is coordinated by using artifacts such as walkie-talkies to achieve a shared and consistent cognition. Different elements of the system that contribute to the DSA are called agents. Each distributed agent contributes to the DSA of the operator. Interestingly, the contribution of each agent in the system has a different impact and developing a suitable comparison methodology to determine the weight of these agents to DSA is a topic yet to be explored. The contribution of each agent, constituting DSA, changes dynamically as per the dynamics of the system or operations. Similarly, during non-routine tasks, for instance start-ups, shutdowns, and maintenance work, the agents, which contribute to the DSA of operators, can be completely different respect to those required under normal operating conditions. Developing a method to evaluate the DSA is complex but at the same time important and effectual.

4. Measurement of DSA

Measuring systemic constructs such as DSA is a challenging task as it focuses on the interaction among multiple actors and control units. The provision of good situation awareness has seen its implementation in the design of systems and the assessment of system performance (Salmon *et al.*, 2009b). One reason that can encourage process designers to modify systems for an improved SA is the possibility of measuring SA both quantitatively and qualitatively (Endsley, *et al.*, 2003). Hence, it is of paramount importance to know how one can measure/assess DSA. To describe and evaluate the DSA of whole systems, Salmon *et al.*, 2009b, proposed the use of semantic or propositional networks that show the connection between concepts that are of relevance to the work task in question.

In a recent article Sorensen and Stanton (2013) measured DSA in 60 five-person teams through the use of a communication analysis that built upon the propositional network methodology. In that study they measured DSA by measuring the amount of relevant concepts that where communicated by the team members during a simulated Command and Control task where the aim was to identify and take red ("enemy") players while avoiding taking non-red (allied) players. They found a very high positive correlation (r = 0.923, p < 0.001) between the number of relevant concepts communicated and the number of taken red players. Indicating that communication of relevant concepts might be a good indicator of DSA. Sorensen and Stanton (2013) also found a negative correlation (r = -0.520, p < 0.01) between measured DSA and the erroneous taking of non-red ("fratricide") indicating that high DSA was a barrier against errors. In short, Sorensen and Stanton's article showed that communication logs are a viable approach to measuring DSA. A recent study, suggests that evaluation of SA can be considered as a learning outcome (Sorensen and Stanton, 2013). According to the authors, nature of process industry, multilevel complexity, interconnections, boundary conditions, operating constraints, control algorithms, nature of job of operators, and distribution of teams call for a different approach to DSA assessment of industrial operators. The DSA of an industrial operator can be evaluated by defining specific performance indicators satisfying the concept and theory of DSA, which we call Distributed Situation Awareness Indicators, DSAIs. The proposed indicators, which allow evaluating the DSA of operators, can be implemented in a computer algorithm for real time analysis (for details see Manca *et al.*, 2012, 2013). However, developing a general methodology for measurement of DSA still seems far from complete, as every industrial process is composed of various and diverse elements. Therefore, while developing a DSA measurement algorithm different agents/factors should be considered. For the scope of this paper, only the following are emphasized: team structures, complexity and nature of the process, safety constraints, operating conditions, and the involved artifacts.

4.1 Team structure

The impact of team structure and its effect on performance and coordination have been studied in command and control and aviation sector (Alberts, 2003). Nevertheless, the importance of team structure is equally important for the process industry. Sorensen and Stanton (2013) demonstrated the influence of different structures of teams and their impact on the performance. The teams in process industry can be categorized into FOPs-FOPs, CROPs-FOPs, CROP-CROPs, CR/FOPs-non-technical staff (Nazir *et al.*, 2012).

4.2 Complexity and nature of industrial process

Different chemical processes demand different sets of communication among FOPs, CROPs and other non-technical team members. Moreover, the frequency of such communication is also a function of nature of plant, interconnections among various components and control loops, area of the plant, type of operations (*e.g.*, refineries, fertilizer, power, nuclear , and polymer plants) and location of the plant (either on-shore or off-shore). The relative significance of communication also changes with the nature of the process and the distribution of different plant subsections, and equally the DSA of operator that should be considered while devising the respective indicators.

4.3 Safety constraints

Safety constraints are important parameters in defining the indicators for DSA. They have a close correlation with the complexity and nature of the plant. At the same time, geographical location and safety culture are also involved in defining such constraints. The challenge here is to identify those indicators that refer to the process safety and at the same time that are responsible for constituting the DSA of operators.

4.4 Operating conditions

Complexity of chemical processes, safety constraints, and operating conditions are interwoven with each other. Therefore, they cannot be considered individually. As mentioned before, the DSA of operators changes according to the operating conditions. Abnormal situations and accident events must be dealt with a different mindset as compared to normal operating conditions. Therefore, defining separate measurement indicators for DSA for both scenarios is necessary (*i.e.* normal vs abnormal). It is noteworthy that the operating conditions, which are deemed optimal during normal operating conditions, can be alarming during abnormal situations or non-routine tasks (like start-ups and shutdowns).

4.5 Artifacts

The interaction of the operator with different tools, information inputs, and sources makes this parameter extremely important and significant. A modern industrial plant consists of large DCSs, hundreds if not thousands of control loops, multilevel interconnections, which the operators need to observe, understand, and optimize. These bits of information are usually equalized and communicated among FOPs and CROPs by means of push-to-talk devices (*e.g.*, walkie-talkies). Furthermore, the input sources of information vary evidently among FOPs and CROPs as shown in Table 1. The indicators for measurement of DSA must account for the artifacts involved in any specific process or chemical plant.

Table 1: Input sources for CROPs and FOPs.

CROPs	FOPs
CCTV (closed circuit television)	Spatial representation hints
Control loops	Olfactory hints
DCS synoptic displays	Auditory hints
Communication with FOP	Alarms in the field or coming from CROP
Alarms issued in the control-room	Communication with CROP
Start-up and shut-down procedures with the sequence and timings of actions and commands	Specific actions required during start-up and shut-down procedures
P&IDs	Other visual or observable changes

Table 2: Steps of the experiment about the accident event simulation.

Steps	Description of the events
1	The FOP is at the C3/C4 separation section of the refinery
2	The excavator hits a pipe and breaks a flange
3	The liquid jet is emitted from the ruptured flange and spreads on the ground creating a pool
4	The pool ignites and generates a fire
5	The FOP alerts the CROP (who interacts with the FOP)
6	The CROP closes a remotely controlled valve (from DCS)
7	The outflow stops but the liquid level in the reboiler starts increasing and reaches the high-level alarm
8	The CROP asks the FOP to open a manually operated valve to decrease the reboiler level and then asks to close it back again (to recover the original operating condition)
9	The reboiler level decreases back to the correct value

5. Case study

A case study replicating a real accident in a refinery subsection (*i.e.* C3/C4 splitter), is discussed to devise DSAIs, in the light of aforementioned concepts and proposed DSA measurement methodology. An experiment was conducted in order to understand, evaluate, and analyze the impact of training on DSA of

operators. The details of the experiment, simulator setup, and scenario are extensively discussed in Manca *et al.*, 2013 and Nazir *et al.*, 2013, whereas the specific details about the impact of training on DSA and the analysis of results will be presented in a forthcoming paper (Impact of training methods on DSA of industrial operators). This manuscript reports a short summary of the steps involved and specifically of the DSAIs implemented. The accident scenario requires the operators to communicate and develop a shared mental model and reach appropriate decisions to minimize the possible consequences of the accident. The main steps of the experiment are summarized in Table 2.
With reference to the events reported in Table 2, the DSA is constructed by various agents, which change dynamically as the accident scenario evolves (see Figure 1).

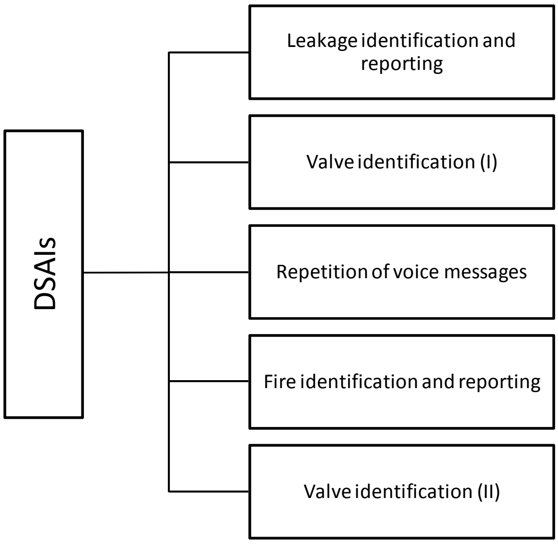

Figure 1: The proposed Distributed Situation Awareness Indicators (DSAIs).

For sake of simplicity, let us consider the "*leakage identification and reporting*" DSAI at the top most of Figure 1. The operator in the field realizes the leakage in the pipe, where a flammable liquid mixture (*i.e.* C3/C4) is flowing. It is a *severe* abnormal situation which must be observed carefully in terms of understanding the nature of the liquid, and location of the pipe and must be reported to the control room immediately, in a clear and intelligible way, for necessary actions. For this case study, the bits of information, which add to DSA in the light of aforementioned concepts, are:

- team structure *i.e.*, FOP-CROP working together;
- complexity of the process *i.e.*, understanding the nature of the leaking fluid and its location;
- anticipating the dynamic evolution of the process, *i.e.* identify the operating parameters that will deviate from their optimal range as a consequence of the leakage;
- safety constraints *i.e.*, flammable liquid and anticipating the possibility of fire;
- artifacts, *i.e.* the walkie-talkie used by the FOP to communicate with the control room and the data appearing on the DCS, which must be interpreted by the CROP in real time.

6. Discussions and implications

The study of DSA of industrial operators possesses more benefits than it apparently shows and may have positive long-lasting impacts on the safety of chemical processes. The investigation and analysis of the accidents, which took place over past years in the process industry, were focused on equipment failure, maintenance issues, and malfunctions (physical). The human role was often overlooked. The outcome of this approach resulted in designs, that did not facilitate human factors in general and operator's DSA in particular. Therefore, the DSA implementation allows the designers considering features that facilitate DSA of operators and allow operators to perform/react in an improved way, especially when the system crosses the normal operating range. Such measures may avert accidents, therefore, the number of accidents per year may be reduced, and the subsequent losses (both human and financial). Moreover, consciously facilitating operators for improved DSA during normal and abnormal situations in the training phase can help in better performance of operators. To achieve this, investigation of DSAIs for various processes can be devised and integrated in the training methods.

Performance indicators and hierarchical methods for evaluation performance is a recent advancement in the domain of training, performance assessment, and industrial safety (Nazir *et al.* 2012, Manca *et al.* 2013). The DSAIs might prove an important step towards embracing these new concepts and incorporating them in the safety of industrial processes. Moreover, once DSAIs are experimentally validated, their impact will be evident and might encourage the related scientific community, process designers, and practitioners to realize its significance.

7. Conclusions

This work can be considered as a starting point for investigation of DSA of industrial operators. The link between DSA and process industry, and a preliminary identification of DSA indicators are the main contributions of this work. Some of the features that can be considered in the development of a measurement method for DSA were highlighted. A case study was reported to present and discuss the topics that were introduced theoretically. The paper paves the way for the development of models of DSA for FOPs and CROPs, the identification of DSAIs for different industrial operations, and weighing criteria of DSAIs. The authors are conducting experiments to determine the impact of training on DSA of industrial operators and measure their performance during critical events. Once the impact of DSA and its implication in the process industry become evident, these features may lead to the adaptation/modification of conventional training methods.

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